

# The Structure of the Local Universe and the Coldness of the Cosmic Flow

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**Abstract.** Unlike the substantial coherent bulk motion in which our local patch of the Cosmos is participating, the amplitude of the random motions around this large scale flow seems to be surprisingly low. Attempts to invoke global explanations to account for this coldness of the local cosmic velocity field have not yet been successful. Here we propose a different view on this cosmic dilemma, stressing the repercussions of our cosmic neighbourhood embodying a rather uncharacteristic region of the Cosmos. Suspended between two huge mass concentrations, the Great Attractor region and the Perseus-Pisces chain, we find ourselves in a region of relatively low density yet with a very strong tidal shear. By means of constrained realizations of our local Universe, based on Wiener-filtered reconstructions inferred from the Mark III catalogue of galaxy peculiar velocities, we show that indeed this configuration may induce locally cold regions. Hence, the coldness of the local flow may be a cosmic variance effect.

## 1. Introduction: Cosmic Migrations versus Local Chills

When speaking in terms of the motions of the objects populating the immediate vicinity of our Local Group, i.e. out to a distance of several tens of Megaparsec, our cosmic neighbourhood represents a rather chilly sector of the Universe. Rather than resembling a buzzing hive of galaxies rushing crisscross through space without any well-defined destination, we appear to be participating in a highly organized and coherent matter stream advancing towards a seemingly preordained direction. These streams are the instruments through which vast amounts of matter get channelled from their initial locations in the pristine and almost featureless primordial Universe towards the sites where matter accumulates in the process of building up the pronounced and complex patterns that nowadays we recognize in the large scale distribution of galaxies. Within the gravitational instability scenario of structure formation, it are the same continuously waxing density excesses and depressions that induce these cosmic migration flows through their combined gravitational action. It is this intimate dynamical link between the distribution of matter, the induced cosmic flows, and the emergence of structure in the Universe that prompted substantial interest in

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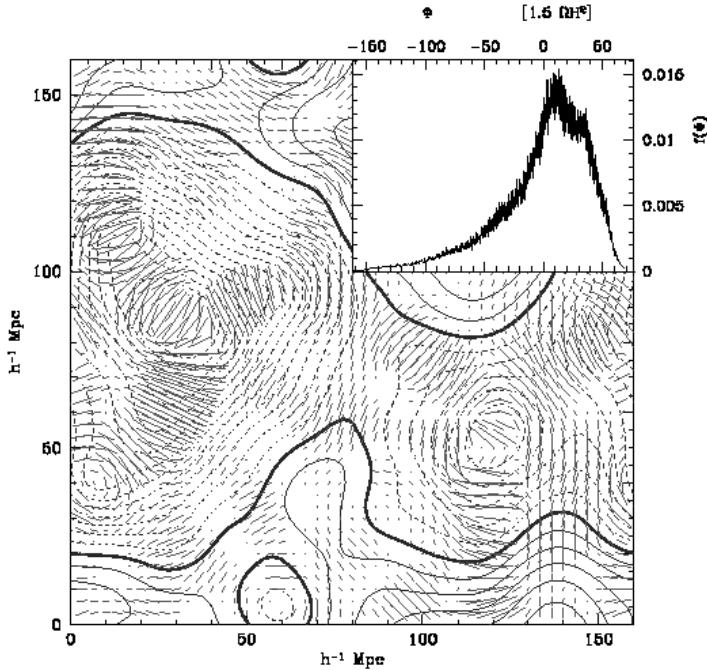


Figure 1. The gravitational potential in the Local Universe: a “bipolar world”. Contours: gravitational potential  $\phi$ . Bars: compressional component tidal shear. Insert: the pdf of  $\phi$ . Details: see text.

the characteristics of the observed cosmic velocity field as useful fossil probes of the structure formation process. The amount of matter residing within the observed structures will be directly reflected in the corresponding matter streams. Hence, in a high- $\Omega$  Universe we expect the cosmic flows to involve higher velocities. This is true on any scale, whether it concerns the large scale bulk motions associated with the assembly of the characteristic foamlike patterns encountered on scales of tens of Megaparsec or structures on much smaller scales, whose dynamical timescales are so short that they have evolved to highly nonlinear stages in which the matter currents got (partially) “thermalized” and therefore lost the memory of their original state.

Early assessment of the small-scale random motions of galaxies, estimated on the basis of pairwise velocity dispersions, revealed that locally the Universe is rather cold. While we participate in a bulk flow of  $\approx 600$  km/s, the random velocities with respect to the mean flow are estimated to be in the range of a mere 200–300 km/s. This low value of the velocity dispersion in combination with the pronounced structure displayed by the distribution of galaxies was in fact a strong argument for the latter being a biased tracer of the underlying matter distribution. The assumption of bias, in particular in the form of the (overly) simplistic linear bias factor  $b$ , would then imply the matter distribution not to have evolved as far as suggested by the pronounced nature of the galaxy distribution, and hence would be in agreement with the low value of the “thermal” motions in the local Universe.

## 2. Potential Eccentricities and Tidal Stresses

In an attempt to interpret the significance of the coldness of the local cosmic flow, we postulate an alternative view. Rather than interpreting the coldness of the flow as a property of the global Universe, we hold the view that the solution of the issue is contained in our rather atypical local cosmic vicinity. Within a distance of a few tens of Megaparsec we have not yet reached a fully representative volume of the Universe. This can be discerned rather straightforwardly from the local galaxy distribution. Even more explicit, however, is the situation when assessing the velocities of galaxies in our cosmic neighbourhood. These velocities reflect the underlying gravitational force and potential field, both having far larger coherence lengths than the density distribution. Hence, the volume probed by peculiar galaxy velocity surveys represents a rather restricted dynamical probe, unlikely to be anywhere near to fairly sampling that of the overall Universe.

Meticulous analysis of the peculiar velocities of galaxies in the immediate cosmic neighbourhood have unveiled the nearby superstructures of the Great Attractor (GA) and the Perseus-Pisces supercluster (PP) as the dynamically dominating protagonists in the local cosmic tug of war. Although there are certainly several other contenders pulling their weight, be it in the form of nearby local structures or far-away monsters like the Shapley concentration, their contribution is unlikely to represent more than a moderate modification to the basic dynamical constellation set by the GA and the PP. Moreover, there does not appear to be any compelling evidence for the existence of dynamically influential mass concentrations beyond a distance of  $\approx 150h^{-1}\text{Mpc}$ .

A telling illustration of this preponderance of GA and PP is shown in the contour map of figure 1. It contains a reconstruction of the linear gravitational potential field (Gaussian scale  $R_f = 5h^{-1}\text{Mpc}$ ) in our local Universe, within a region of size  $160h^{-1}\text{ Mpc}$  centered on our Local Group. Shown is a planar section approximately coinciding with the Supergalactic Plane. It is based on the set measured peculiar velocities of galaxies in the Mark III catalogue (Willick et al. 1997), processed by means of the Wiener filter reconstruction technique developed by Zaroubi et al. (1995). Evidently, the gravitational potential is dominated by two huge potential wells, the Great Attractor on the lefthand side and the Pisces-Perseus supercluster region on the righthand side. Also the pdf of the gravitational potential (insert figure 1), displaying an atypical shoulder, corroborates the atypical nature of the local gravitational potential. Moreover, seemingly we find ourselves located right near the centre of a configuration strongly reminiscent of that of a canonical quadrupolar pattern, with two massive density enhancements along the horizontal axis and void regions concentrated around the perpendicular bisecting plane. The direct implication of the morphology depicted in figure 1 is that we are located near the saddle point of strong field of tidal shear. The red edges in figure 1, superposed on the potential contours and having a size and direction proportional to the strength of the compression along the indicated direction, represent the compressional component of this implied tidal force. Evidently, the tidal shear is very strong within the realm of the two huge matter concentrations where the density reaches high values. Very important to note, however, is that we also see that the tidal shear is indeed very strong near our own position, a region of rather modest den-

sity, due to the fact that we are located roughly halfway in between the Great Attractor and the Perseus-Pisces chain.

Such a region of moderate to low local density in combination with a strong external tidal field may be expected to experience a different kinematical evolution from that of a similar isolated site. Its contraction will not only be dominated by its own selfgravity, external tidal forces of a similar order of magnitude will substantially shear the corresponding matter flows and lead to an anisotropic collapse. Although collapse may be accelerated along the compressional direction (Icke 1973), the shearing along the other directions may readily delay virialization and thus yield an ungenerically cold region.

### 3. Cosmic Moulding

To assess the viability of the heuristic picture sketched in the preceding section, we set out on an exploration of the kinematical evolution of a Local Group like region in an appropriate large-scale setting. The issue at stake involves the “thermalization” of a small-scale feature like our Local Group, definitively a non-linear phenomenon, but also the influence of large-scale linearly or quasi-linearly evolving structures setting the external force field. No analytical approximations are known that would describe such situations to any satisfactory extent. This prompted our investigation by means of N-body simulations of the evolution of configurations resembling the local cosmic vicinity. Of crucial importance to this study is the issue of an appropriate representation of the local Universe. We might restrict ourselves to some of the known properties of the Local Group, as for instance the density perturbation it represents, its peculiar velocity of 600 km/s, or maybe even some additional environmental requirements like the presence of a few nearby massive clusters. However, as indicated by e.g. Van de Weygaert & Bertschinger (1996) such single localized constraints still leave ample freedom for the overall matter distribution. So much freedom that we cannot be guaranteed of actually assessing the appropriate cosmological situation. We would not be able to assure the correct spatial extent and structure of the large scale environment and consequently would also fail in having the correct temporal development of the local force fields. Because we argue that it is precisely the collusion between the specific localized conditions and the particular configuration of the the large-scale environment that may offer the explanation for the coldness of the local cosmic flow, we choose to set up optimally moulded initial conditions for our simulations instead of taking large random realizations and searching for objects that appear to be rather similar to our own Local Group.

Focussing specifically on the dynamical and kinematical evolution of the local Universe, we invoke the observational information yielded by surveys of galaxy peculiar velocities, arguably the best available objective source on the mass distribution in the cosmic neighbourhood. On sufficiently large scales these velocities reflect directly the mass distribution, so that we can use them to distill an optimally significant reconstruction of the prevailing primordial linear density field in the local Cosmos. We achieve this by applying a Wiener filter algorithm to the sample of measured peculiar velocities of galaxies in the Mark III catalogue (Willick et al. 1997), yielding a reconstruction that is optimal in terms of having a maximum signal/noise ratio (see Zaroubi et al. 1995). The

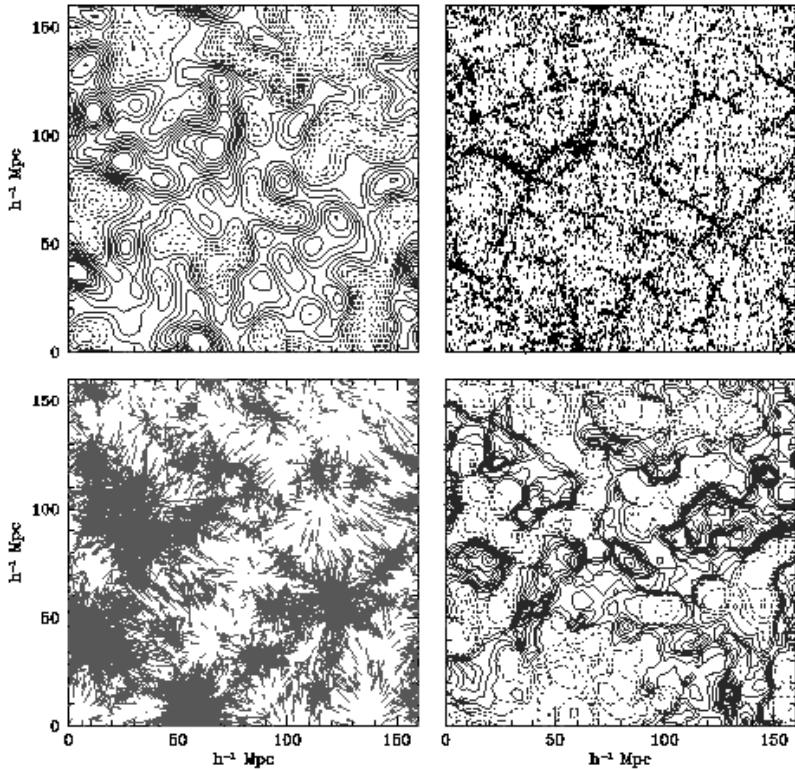


Figure 2. Illustration of a computer realization/simulation of the local Universe. Top left: contour map initial density field. Top right: particle distribution at present epoch ( $a_0$ ). Bottom left: particle peculiar velocities at  $a_0$ . Bottom right: contour map of local cosmic Mach number at  $a_0$ .

Wiener filtered field in Figure 1 represents our cosmic environment on linear scales of  $R_f > 5h^{-1}$  Mpc. Such a reconstruction restricts itself to regions that are still within the linear regime, and whose statistical properties are still Gaussian.

We discard further observational constraints on the small-scale clumpiness and motions in the local Universe. Instead, we generate and superpose several realizations of small-scale density and velocity fluctuations according to a specific power spectrum of fluctuations, with a global cosmological background specified by  $H_0$  and  $\Omega_0$ , and with the small-scale noise being appropriately modulated by the large-scale Wiener filter reconstructed density field. To this end we invoke the technique of constrained random fields (see Hoffman & Ribak 1991, van de Weygaert & Bertschinger 1996), with the Wiener filtered field,  $\mathbf{s}_{wn}$  = playing the role of “mean field”. This setup allows us to test the likelihood of a cold local patch of the Universe embedded within a large scale environment reminiscent of the observed one in the local Universe.

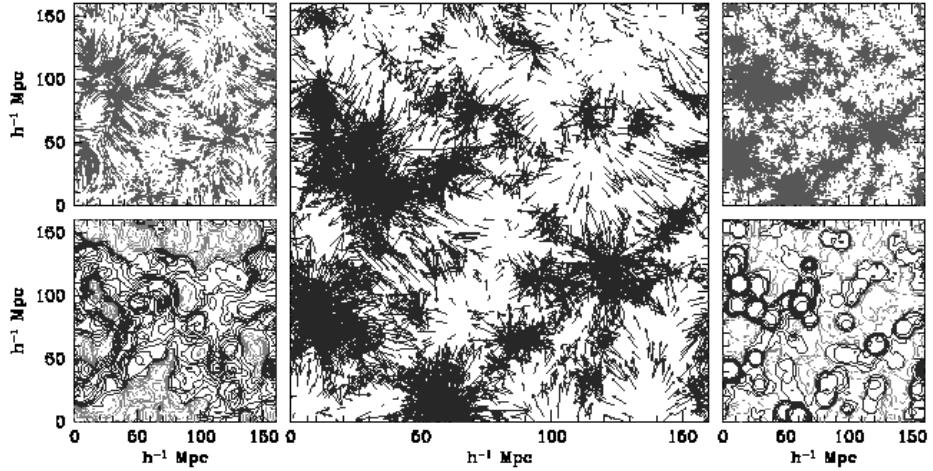


Figure 3. Decomposition of the local velocity field (central frame) into the large-scale bulk velocity (lefthand frame) and residual small-scale “velocity dispersion” (righthand frame).

#### 4. Local Universe in a computer shell

A particular constrained realization of a patch of the Universe resembling the primordial density field in our local cosmic neighbourhood is depicted in the upper lefthand frame of figure 2. It concerns a constrained realization of our Local Universe for the Standard Cold Dark matter scenario, with  $\Omega_0 = 1.0$  and  $H_0 = 50 \text{ km/s/Mpc}$ . Its subsequent evolution is followed by means of the a P<sup>3</sup>M N-body code. The resulting distribution of the particles in a central slice through the simulations box is shown in the upper righthand frame of figure 2. Clearly recognizable are massive concentrations of matter at the locations where in the real Universe we observe the presence of the Great Attractor region (slightly “north” of the “west” direction) and the Perseus-Pisces region (slightly “south” of the “east”). Interesting is to see how vast and extended these regions in fact are, certainly not to be identified with well-defined singular objects.

#### 5. The local cosmic weather: Cool and Stormy

The corresponding velocity field is shown in the lower lefthand frame. To appreciate the small-scale and large-scale contributions to the peculiar velocity field, in figure 3 we have decomposed the full velocity field (central frame) into the large-scale bulk flow  $\mathbf{v}_{bulk}$  (lefthand, vectors in the top frame, amplitude contour plot in the lower frame) and the residual small-scale “velocity dispersion”  $\mathbf{v}_\sigma$  (for technical details see Van de Weygaert & Hoffman 1999). The decomposition criterion is set by top-hat filtering the velocity field at the scale of nonlinearity,  $R_{TH} = 8h^{-1}\text{Mpc}$ . Note the striking matter displacement pattern revealed by the bulk flow

field and its close relationship to the large-scale features emerging in the particle distribution (figure 2). Equally interesting is the fact that also the small-scale velocity dispersion field appears to bear the marks of underlying large-scale

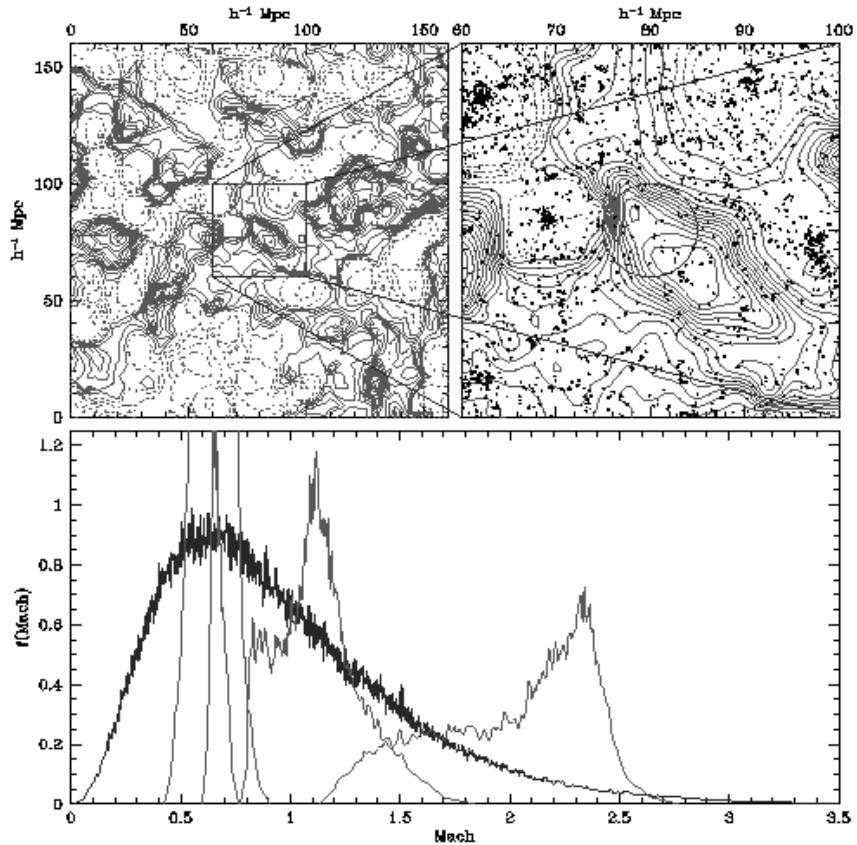


Figure 4. Zooming in on the Mach number field in figure 2 (top frames). The global  $\mathcal{M}$  pdf (solid), with a superposition of four locally determined pdf's (within sphere depicted in top righthand frame).

features: not only do we see substantial “thermal” velocities at the sites of cluster concentrations, but we can also recognize sizeable small-scale velocities near the locations of filaments. When we compare the contour plots of the bulk motion and the dispersion velocities, we can already discern the fact that while we – located at the centre of the simulation box – are embedded in a region with high bulk flow, evidently incited by the GA and the PP region, but that we also find ourselves in a region of exceptional low velocity dispersion. Indeed a telling reproduction of the observed “coldness” of the local cosmos. Assessing the relative large-scale and small-scale contributions to the velocity field, we quantify the “coldness” of the cosmic flow by means of the ratio between the local bulk flow velocities  $|\mathbf{v}|_{bulk}$  and the “dispersion” velocity  $\sigma(\mathbf{v})$ ,

$$\mathcal{M} \equiv |\mathbf{v}|_{bulk}/\sigma(\mathbf{v}) . \quad (1)$$

yielding a quantity whose cosmic average was introduced as “cosmic Mach number”  $\mathcal{M}$  by Ostriker & Suto (1990). They propagated this quantity as a useful and complementary characterization of structure formation scenarios, quantifying the relative contributions of large and small scale matter perturbations with

the great virtue of being insensitive to the amplitude of the power spectrum of density perturbations. We, however, are not so much interested in the cosmic average as well as in the spatial distribution and coherence of the point-to-point Mach number  $\mathcal{M}(\mathbf{x})$ , and its relation to the underlying matter field. For the simulation mentioned above and illustrated in figure 2 and figure 3, we show the spatial structure of the Mach number field in the lower righthand frame of figure 2. A comparison with the corresponding density map reveals the interesting aspect of a large coherent band of high Mach number values running from the lower lefthand side to the upper righthand side of the simulation box, avoiding both the Great Attractor region and the Pisces-Perseus region, situated approximately in between those two complexes. Superposed on this large-scale pattern are a plethora of small-scale features. For our purpose the most significant of these is the fact that we – situated near the centre – appear to be right near a towering peak of the Mach number distribution. Zooming in on the Mach number field we can readily appreciate this in figure 4, in the contour map frames. We should note that as the cosmic environment was specified on a scale of  $R_g > 5h^{-1}\text{Mpc}$  we cannot really accurately pinpoint our own location to within a region of a similar size. In this respect it is very interesting to see a small Local Group size clump of particles near the peak of the Mach number distribution (top righthand frame fig. 4). It might indeed be the ultimate illustration of a Local Group like object, cold, relatively isolated, but member of a huge coherent complex. Even within a high- $\Omega$  Universe such a configuration may lead to an uncharacteristically cold situation. This can most clearly apprehended when comparing the global Mach number one-point probability distribution in the bottom frame of figure 4 with the distribution in limited central regions (sphere in the top frame). Superposed on the global pdf are distributions from central regions in four different realizations, the most shifted one corresponding to the simulation illustrated in the previous figures. Evidently, in two cases nothing exceptional is observed, but in two other cases we observe uncharacteristically “cold” environments. Hence, the atypical local velocity field realization may make us prone to infer flawed conclusions with respect to the global Universe, and we should take care to take into account the rather particular spatial local matter configuration in which we are embedded.

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## References

- Hoffman, Y., Ribak, E., 1991, ApJ, 380, L5
- Icke, V., 1973, A&A, 27, 1
- Ostriker, J.P., Suto, Y., 1990, ApJ, 348, 378
- van de Weygaert, R., Bertschinger, E., 1996, MNRAS, 281, 84
- van de Weygaert, R., Hoffman, Y., 1999, ApJ, submitted
- Willick, J.A., Courteau, S., Faber, S.M., Burstein, D., Dekel, A., Strauss, M.A., 1997, ApJS, 109, 333
- Zaroubi, S., Hoffman, Y., Fisher, K.B., Lahav, O., 1995, ApJ, 449, 446